

Evaluating Feasibility of Energy Consumption Monitoring in Residential Energy Assessments

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Many existing homes in the United States waste energy due to various inefficient systems, energy consumption behaviors, and construction deficiencies. A great potential exists for homeowners to reduce their energy expenditures, which can be achieved through energy retrofit solutions applied to homes. Decisions to pursue a retrofit action in a home are commonly based upon energy assessments provided by auditors, who utilize a mix of diagnostic tools, inspection strategies, evaluation practices, and energy modeling simulations. Although a variety of energy assessment methods are available today helping identify the most promising retrofit opportunities, many barriers and issues still exist for homeowners to take action. One significant factor contributing to homeowners reduced confidence is a lack of energy assessment accuracy, which has led to a lack of retrofit decision-making. This study investigated the use and practicality of energy consumption monitoring, an assessment method less commonly used by energy auditors, but can provide greater accuracy. Using measured data, consumption and savings potentials were estimated based on occupant use behaviors for gas fired domestic hot water heaters. The findings identified the feasibility and applicability of this type of method towards improving energy assessment accuracy, increasing stakeholder confidence, and promoting more active retrofit decision-making.

Key Words: Energy Consumption Monitoring, Energy Assessments, Residential Retrofitting

Introduction

According to United States (U.S.) Census data, approximately 61% of homes in the U.S. were constructed before 1980. Of these homes, 60% of the energy used by them for heating and cooling is lost due to leaky ducts, inefficient equipment, poor insulation and air leaks (ETO, 2008). The U.S. Department of Energy reports that only 20% of the homes built before 1980 are well insulated (DOE, 2011). The issues concerning the current energy performance in many older existing homes built before 1980 are emptying homeowner's pockets, spending a reported 118.86 billion dollars annually on energy (EIA, 2005). As the adoption and use of technology continues to increase, residential energy consumption is also expected to rise. This high number of homes built before 1980 also reveals the need for residential retrofitting and the opportunity it presents for many of the involved stakeholders, which includes homeowners, auditors, and home builders/retrofitters. In a report prepared by the White House Council on Environmental Quality (CEQ), it was proposed that home energy efficiency retrofits have the potential to reduce home energy bills by 21 billion dollars annually, ultimately paying for themselves over time (CEQ, 2009). The potential business gained by auditors and builders through retrofitting can also similarly grow if the desire for retrofitting increases.

Homes use approximately one fifth of the total energy consumed in the U.S., and this figure has been increasing steadily since 1985 (USGBC, 2011). This increase could also possibly be due to other sectors that may have been saving energy more proactively, or perhaps a faster growth in housing creation than other sectors such as transportation. Even so, the total energy consumed by homes in the U.S. does not take into account the energy used for transportation, production, and other associated processes with materials and equipment used in the residential construction industry, which would dramatically raise that fraction. The new technologies, products, incentives and techniques being developed and currently used in today's residential energy efficiency market can reduce energy consumption in many ways. This includes solutions such as improved insulation systems, more efficient heating and cooling technologies, and installing Energy Star® appliances and household items, all of which can also lead to substantial monetary savings due to improved energy performance. But even with all of these available resources and incentives, why are many homeowners not taking advantage of home energy retrofits and reaping the rewards?

One possible problem contributing to this could be the step prior to retrofitting their existing spaces, the diagnosis. This problem refers to the assessment results a homeowner receives from an energy audit of their home, which identifies energy inefficiencies and areas for improvement in and around their homes related to energy consumption. For example, if the assessed and/or simulated assessment results differ significantly from the homeowner's actual energy consumption, the confidence in any retrofit suggestions and associated savings proposed by a tool or auditor may be very low. In other instances, where a discrepancy is not identified, a homeowner might draw wrong conclusions and invest in less profitable scenarios, and subsequently consider energy efficiency measurements as unreliable to a broader public as shown in numerous blogs and comments provided on sites such as GreenBuildingAdvisor.com.

Residential energy assessments today have various unresolved issues, which in turn have contributed to homeowners reduced confidence in energy assessments and a lack of retrofit decision-making. These problems range from inefficient and inaccurate auditing practices and tools, differing opinions and perceptions from auditors, and auditors who may not be properly trained (DOE, 2011). Current methods in home energy assessments lead to failures and missed improvements resulting in lower-than expected savings, no savings, and even in some cases, higher energy use (Shapiro, 2011). There is a set of common tools and practices used for residential energy assessments that target different areas of energy efficiency in the home such as a blower door, thermal imaging, and air infiltration measurement tools. These are intended for the purposes of assessing parameters such as building envelope heat losses, thermal gains, pressure differences, infiltration, ventilation, and energy consumption from building systems and appliances. An auditor may choose to use one, or a combination of practices and tools, that could possibly inaccurately target or be unable to assess the areas where a home is most energy inefficient. Similarly, an auditor may not have the means, access, or training to use certain assessment tools and practices that could identify where the home is most inefficient in energy use. If a variety of tools and audit practices are not used when performing a home energy audit, crucial indicators of inefficiency may be overlooked. There are many other factors that can contribute to the difficulty of producing accurate assessment results. Assessments can include time consuming processes, varying complexities in house geometry, complicated duct system layouts, and old appliances (EAI & CSG, 2009)

For increased accuracy, including occupant behavior use patterns in an energy assessment for analysis can provide important user specific results for retrofit decision-making. It has been concluded from various studies that including occupant use behavior in an energy assessment can significantly increase the accuracy of an assessment, as well as increase the motivation for homeowners to seek an energy assessment on their home (Clevenger & Haymaker, 2006); (Ingle et al., 2012); (Durak, 2011). Asset based assessments, or assessments that include a minimal amount of occupant use behavior data, can cause key assessment criteria to be overlooked or distorted. This is an important consideration when selecting assessment tools to ensure a misuse is avoided. In a report prepared for the DOE, common traits and factors that appear to influence the success of home energy retrofit decisions based on energy assessment results were investigated. One of the conclusions made from the study was that current energy assessment tools and practices are not designed to detect behavioral patterns (Lancaster et al., 2012).

With difficulty being experienced by auditors, as well as the prevalence of problematic assessment tools, practices, and omitted critical assessment data, this leads to a lack of reliability in retrofitting and its promise of energy and monetary savings in return. The time and money spent on auditing homes also serves as a hindrance towards retrofitting, with many homeowners not wanting to invest in a process that could potentially lead to no earned value. Therefore, in order to solve these problems, it is important to understand and investigate what is most effective, and what can be improved upon to greater benefit residential retrofitting potential and its stakeholders. Homeowners should be saving money and lowering their energy consumption through retrofitting. They look at their large energy bills hoping to lower them, but do not know what to do first to achieve this. This task is made especially difficult for homeowners due to the vast selection of assessment methods to select from, the many influences that can be taken into account, and the many tools and practices being identified, or speculated, as unreliable. Reassurance and refinement in residential energy assessments is a must.

Study Purpose

By using a combination of various energy assessment methods, an energy auditor can go into a home and provide a good evaluation of a home's energy performance to be used for retrofit decision-making. But the issue with accuracy still remains. It has been determined that utilizing more in depth occupant behavior data in energy assessments can not only increase the accuracy of results, but promote more active retrofit decision-making by increasing the amount of confidence in assessment results.

The purpose of this study was to go beyond the standard assessment of occupant behavior and usage data (i.e. surveys and questionnaires) and to go into greater depths using an audit method that micrometers and monitors actual energy use of an appliance and thus can derive behavior patterns in a home. While many tools exist for electricity driven appliances, for gas fired appliances micro-metering is typically not an applicable option in homes. By conducting this study, it was the goal to evaluate the feasibility of individually monitoring the consumption of gas fired hot water heaters for an energy assessment, and to also investigate the potential of this method to provide more clarity and accuracy.

Common methods of measuring domestic hot water energy consumption that have been evaluated and conducted in previous studies (Harrington, Lane, & Wilkenfeld, 2010) (Aguilar, White, & Ryan, 2005) (Energy Monitoring, 2008) have included taking flow measurements and monitoring hot water drawoff at a hot water tank with supporting temperature measurements taken at the main piping branches; temperature based inference, which involves taking temperature measurements as close as possible to specific use points; surveying household members regarding their occupancy behaviors; and measuring cold feed pipework temperatures with probe sensors. Similar to previous studies, temperature probe sensor measurements at pipework connected to the hot water tank was the method used to collect hot water usage data for analysis to estimate energy consumption. This investigation is a part of a larger effort towards improving energy assessment accuracy, as not all assessment methods require close scrutiny towards occupancy patterns, such as calculating air infiltration. Interviews conducted with several energy auditors located in Blacksburg, VA revealed an accord for energy consumption monitoring as a potential benefit to their own processes, a method they do not currently use (Ladipo, Reichard, McCoy, & Pearce, 2013). Energy consumption monitoring is a type of energy assessment method that is not commonly used on typical energy audits, although the level of detail they can provide has the potential to significantly increase accuracy.

Method

To address some of this curiosity, as well as to investigate an energy assessment method not typically implemented by energy auditors, a gas hot water heater was monitored in a single-family home to evaluate its energy consumption. Two adults, one teenager, and two young children occupy the house located in Blacksburg, VA. The hot water heater's temperature fluctuations measured from the hot and cold water pipes and burner were monitored and recorded using Onset HOBO® Data Loggers and temperature sensors. A data logger is an electronic instrument used to monitor building systems performance by recording measurements such as temperature, relative humidity, light intensity, air quality, voltage, and amperage over extended periods of time while unattended (Daly & Flye, 2000). The energy consumption of the monitored hot water heater was estimated through a series of calculations using the measured data collected from the loggers. By conducting this experiment, it was the aim to identify patterns that reveal occupancy load, base load, and peak load for the specific consumption item and its context. Context includes the occupancy rate, household composition, the type of home, and the associated climate conditions, all of which have been identified as important influences on domestic hot water energy consumption (Aguilar et al., 2005). By calculating the energy required to heat the hot water in the storage tank, this process also has the potential to disambiguate utility bills if applied to other systems and appliances in a home using similar strategies.

A total of three temperature sensors were attached to the gas hot water heater tank in three different positions connected to a wireless data logger. The data logger recorded the measurement data and passed them on to a wireless receiver. One temperature sensor was placed on the hot water outlet pipe, a second one on the cold water inlet pipe, and the third on the gas pipe located close to the water heater burner. Images in Figure 1 highlight with circles where each sensor was placed. The data receiver could be placed up to 100ft from the data loggers, which simplifies the installation in tight utility spaces. Data from the receiver was then transferred to the Onset HOBO®node Manager software installed on a laptop computer connected directly to it via a USB port. The software installed on the laptop instantly displayed real time data measured on a scaled temperature vs. time graph for easy viewing and analysis. Data measured by the loggers was then exported into a spreadsheet document for analysis and interpretation. The hot water heater was monitored for one month, which provided sufficient data to visualize how the household consumes hot water through repeated occupant use patterns.

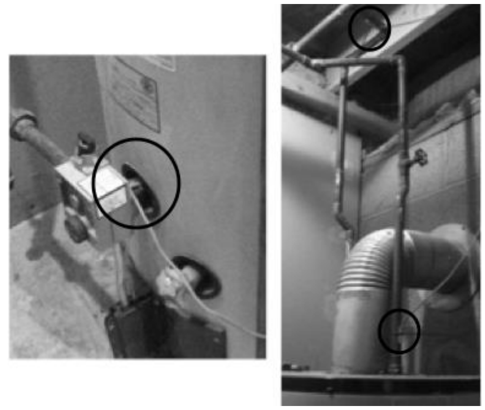

Figure 1: Sensor Locations

Results

Using the exported monitored data, separate graphs were created for this pilot assessment study to represent the cold water demand, hot water demand, and the hot water heater (burner). The data was separated into 24-hour intervals for each category to represent the tank activity over the course of a day. Data for five consecutive weekdays in each category were overlaid on top of each other to reveal occupant behavior patterns during the course of one week out of the month. Examples of this can be seen in Figures 2, 3, and 4. Where patterns closely align with each other when overlaid, use patterns can be identified.

As hot water is demanded, cold water simultaneously enters the tank. This can be seen in Figures 3 and 4 where the temperatures move in opposite directions simultaneously. The burner data (Figure 2) provides perhaps the most revealing and useful data. As hot water is demanded cold water enters from the bottom of the tank, which is represented on the burner graph when the lines sharply dip in temperature before rising again. This occurrence triggers the gas burner to fire and to begin heating the water inside the tank, which has meanwhile cooled below the thermostat setpoint due to the addition of cold water as hot water leaves the tank and is transferred to the demoing fixtures throughout the house. These spikes occur several times throughout the day, and similar patterns repeat daily. The burner fires in the morning, when the occupants begin their day as shown between 6AM and 9AM. In the afternoon during the week, hot water is sometimes demanded if an occupant is at home. In the evening, when most occupants have returned home during the week from work or school, the burner fires again. And finally, the burner triggers once again close to midnight when the dishwasher is started before all occupants retreat to bed. As seen in Figure 4, there were some instances where temperatures rose to 120°F on the cold water pipe sensor. This may seem unreasonable at first glance, but it was the planned intent to separate intake times from static times when collecting sensor data. The sensor measuring the cold water temperature was placed in proximity to the cold water inlet pipe to observe times when cold water was actually present within the pipe versus times when no cold water flow was taking place within the pipe. When no cold water flow was taking place, heat proceeded to flow back from the tank into the cold water inlet pipes by way of conduction, the reason for the 120°F readings.

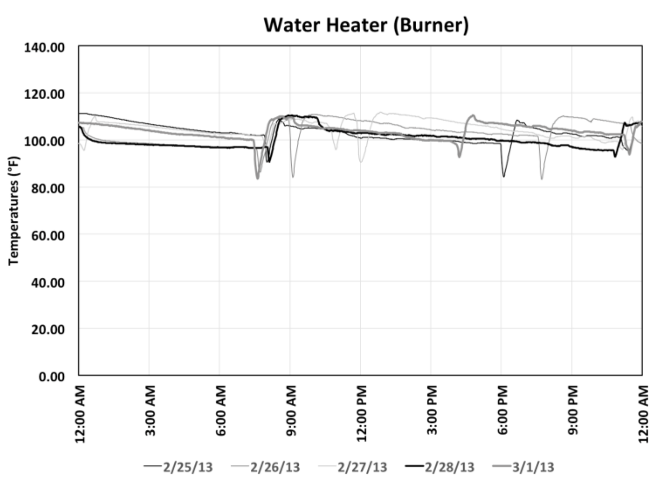

Figure 2: Burner Temp. (2/25/13 – 3/1/13)

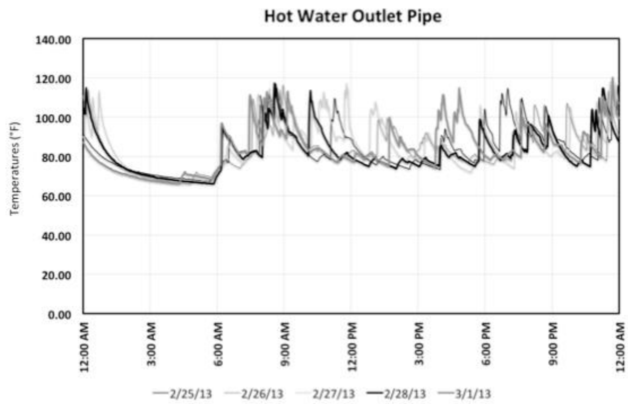

Figure 3: Hot Water Temp. (2/25/13-3/1/13)

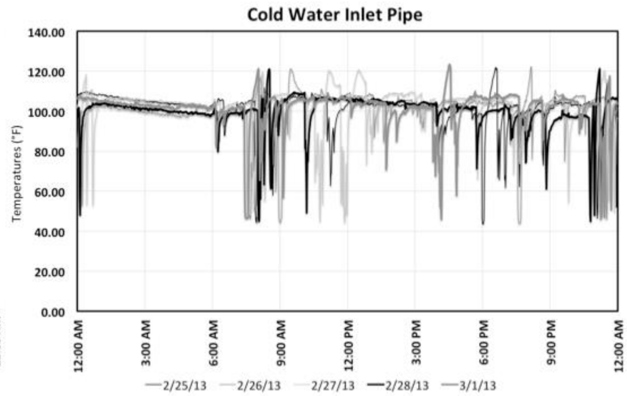

Figure 4: Cold Water Temp. (2/25/13-3/1/13)

Calculating Actual Hot Water Heater Energy Consumption and Heat Loss

Figure 5 represents the measured water heater temperatures (cold water, hot water, and burner) throughout the day on 3/4/13. By analyzing this data the total energy required to reheat the water in the tank can be estimated. The heat loss of the tank can also be estimated and used to identify savings potential and retrofit recommendations based on actual occupant use behaviors rather than using estimated values and assumptions.

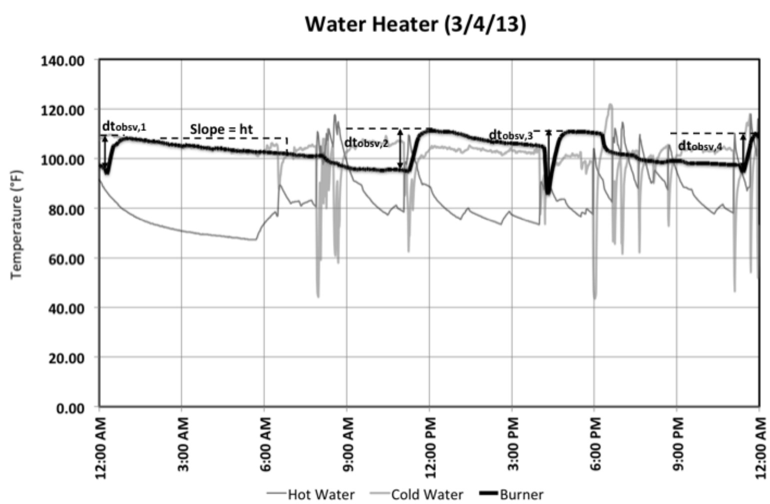

Figure 5: Water Heater Temperature Data (3/4/13)

The energy required to heat water for the occupants of the study house was calculated using the following equations, and values were derived from use patterns of the hot water heater identified (Figure 5). $\mathbf{Q = m \cdot c \cdot \Delta T}$ is the equation used to calculate the energy to change the temperature of water where:

Q = heat energy [BTU]; m = mass of the water [lb]; c = specific heat of water [BTU/lb·°F];

ΔT = water temperature differential [°F]

In order to calculate the value for the total energy (Q_{tot}), the energy consumption for both standby losses (Q_{sta}) and consumption losses (Q_{con}) must first be calculated separately and then added to determine Q_{tot}. The temperature differentials (ΔT) can be found using measured data that were collected over several days and can then be evaluated on per day use for the burner. The specific heat of water (c) is a constant value and is given with 1.0 BTU/lb·°F. The mass of water (m) is found by assessing the number of gallons the water tank can hold, which in this case is 50 gal.

The temperature differential resulting from consumption (ΔT_{con}) can be obtained as the sum of the temperature differences observed when hot water is demanded ($\Delta T_{con} = \Sigma\, dt_{obsv,i}$). The assumption is that as cold water enters the tank it mixes with the hot water and thus drops the total temperature in the tank. This in turn triggers the burner that now has to reheat the lower mixed temperature of the total volume in the tank back to the setpoint temperature. There could be some error in assessment of temperature since the entering cold water could drop the measured temperature before the water in the tank gets mixed.

The drop in standby temperature ΔT_{sta} is the difference experienced when there is no hot water demand, which can be observed during inactive night hours. ΔT_{sta} can be calculated from the average temperature slope (ht) in [°F/hr] observed during non-consumption hours. For the daily standby consumption the slope can now be multiplied with 24 [hr] as a constant linear loss per day. Therefore, $\Delta T_{sta} = ht \cdot 24$. Refer to Figure 5 for visual representation of how these values were derived from the data, where:

$ht = \Delta T_{night}/hr = [°F/hr]; \Delta T_{sta} = ht \cdot 24 = [°F]; \Delta T_{con} = \Sigma\, dt_{obsv,i} = [°F]$

It was found that the total energy required for standby losses (Q_{sta}) on March 4th, 2013 was equal to 9,996 BTU, and the total energy for the observed consumption losses (Q_{con}) was equal to 21,241.5 BTU. The following calculations exemplify how these values were found:

$ht = (108°F – 101°F) / 7hrs = 1.0°F/hr$

$\Delta T_{sta} = 1.0°F/hr \cdot 24hrs = 24.0°F$

$\Delta T_{con} = (108°F – 96°F) + (111°F-95°F) + (111°F-88°F) = 51°F$

It should be noted, that the regularly observed reheating cycle around midnight (due to dishwasher use) was showing up twice for this day (12:15am and 11:30). Thus observation $dt_{obsv,4}$ was omitted for this initial calculation. Ultimately, consumption measurements would be averaged over several days.

$Q_{sta} = m \cdot c \cdot \Delta T_{sta} = (50 \cdot 8.33) \cdot 1.00 \cdot 24 = 9,996$ BTU

$Q_{con} = m \cdot c \cdot \Delta T_{con} = (50 \cdot 8.33) \cdot 1.00 \cdot 51 = 21,241.5$ BTU

An additional step can be taken to calculate a more accurate value for the energy required for the tank to heat the water by adjusting for the efficiency of the heater. For this hot water heater, the efficiency factor is given with 0.90. The final consumption would then equal:

$\mathbf{Q_{tot}}$ = (9,996 + 21,241.5) / 0.90 = **31,237.5 BTU**

From this calculation based on actual consumption data, an estimation of how much money is expended on the hot water heater each month can be found. This can be done by multiplying the total calculated for one day by the total number of days in the month. Ideally, this should be done on averaged data observed over several days. This approach also assumes consistent consumption behavior patterns while the seasonal variations remain relatively small for a water heater located within the conditioned space. For this specific hot water heater the total cost per month extrapolated from the use patterns shown for March 4th 2013 are estimated as follows:

(Conversion factor for therms to BTU assumed with 100,000; Conversion factor for CCF to therms = 1.023)

(31,237.5 BTU) / (100,000therms) = 0.312 therms

$1.81/CCF (Blacksburg natural gas cost) · 1.023 = $1.85/therms

$1.85/therms · 0.312 therms = **$0.58/day (approximately $17.98/month, or $215.76/year)**

Actual utility costs for the study home indicates that gas purchased solely for the hot water heater (observed in non-heating seasons) is approximately $11 per month, as compared to the calculated cost extrapolated from the short term measured data of $18 per month. The EnergyGuide® listed on the hot water heater tank for this study states that based on the national average (natural gas cost listed with $0.56/therm) the estimated average annual cost for that model of hot water heater would be $171, which is slightly less than the calculated annual cost of $215.76. However, a closer look at the EnergyGuide® label revealed that the provided consumption data are from October 1988, so the average gas prices have meanwhile changed significantly.

If the annual cost provided by the EnergyGuide® label is adjusted to current energy prices, the hot water heater annual cost would be closer to $567, which is significantly more than calculated by the assessment method discussed here and even more than the observed utility cost. This large discrepancy makes the usefulness of cost estimates on energy labels questionable, as the authors would assume that a fully occupied household with a family of five should not be so far off the national average in consumption.

Additional steps that can be taken using this data include determining the actual R-value of the tank insulation in lieu of referencing standard or given material values. This can be used to determine excess heat losses that should be captured by the insulation's expected R-value, and used to assess ways to reduce the losses.

Discussion

The time and effort put into conducting this monitoring experiment and energy assessment were considerable. It involved activities such as getting access to the appropriate tools, equipment, and software to conduct the experiment; mounting the data loggers and sensors, and syncing them with the monitoring software; monitoring the data for at least one month to identify clear patterns in consumption that were useful in assuming a typical occupancy use schedule; extracting and analyzing the data from the data loggers and software; and finally, calculating energy consumption and cost estimates. While this assessment technique can lead to a much more accurate energy consumption estimate towards calculating savings and making retrofit/savings recommendations, in its current configuration it does not seem to be a practical strategy for auditors due to the time and cost involved, which can be extensive. This is particularly true when results produced from energy modeling assessments performed on several area homes did not reveal any significant or volatile patterns for water heating consumption, unlike differences observed for the heating ventilation domain (Ladipo et al., 2013).

Although the feasibility of an assessment such as this one conducted on a gas hot water heater is not the most efficient in its current form for auditors, there could be possibilities to develop this process into a method and testing device that simply “snaps on” to a hot water pipe leaving the tank, which could be of great benefit in terms of improving accuracy with estimates and disambiguating utility bills. A similar process connecting to an HVAC duct, could monitor, extract, and analyze data, for the heating and cooling domain and could be of great benefit for auditors. This process could possibly also assist in energy assessment report formats by illustrating projected improvements based on current use that is easy for homeowners to visualize and interpret. Additionally, this method could act as an aid in other areas where energy auditors may be ‘flying blind’, such as revealing occupancy consumption patterns without the need for extensive interviews with homeowners, or reducing the need for educated guesses. Limitations of this study would need to be addressed before developing such strategies further. Seasonal variations were not taken into account when analyzing these studies, as this was conducted as a pilot study and the impact of ambient temperatures for hot water heaters operated within conditioned spaces is considered to be rather small. Some research has shown the importance of considering the effects of events such as weather variations on hot water energy consumption, but mixed among many other variances such as vacations, and changes to family structures (Gladhart & Weihl, 1986). Other limitations of this study included interpolating sensor data to represent actual water temperatures, and the exclusion of weekend occupancy behavior patterns, which were not perceived significantly different in this study, but can differ considerably in other family structures.

In addition to this study, it was initially planned to investigate this method with other utilities and appliances in a home as an attempt to disambiguate the utility bills to further evaluate accuracy. The additional investigation would have evaluated how much each consumption domain actually consumes and ultimately costs out of the total billing cycle. However, due to the extensive time and resources required, this was not achievable within the time frame of this project. It is planned to conduct this experiment in a larger number and variety of applications to evaluate potential ways how this assessment can be developed into a more feasible process for energy auditors.

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